DEEP IMPACT MISSION DESIGN

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Abstract. The Deep Impact mission is designed to provide the first opportunity to probe below the surface of a comet nucleus by a high-speed impact. This requires finding a suitable comet with launch and encounter conditions that allow a meaningful scientific experiment. The overall design requires the consideration of many factors ranging from environmental characteristics of the comet (nucleus size, dust levels, etc.), to launch dates fitting within the NASA Discovery program opportunities, to launch vehicle capability for a large impactor, to the observational conditions for the two approaching spacecraft and for telescopes on Earth.

Keywords: comets, space missions, mission design, 9P/Tempel 1

1. Mission Summary

The Deep Impact mission explores the interior of comet 9P/Tempel 1 by using a 364-kg impactor to excavate a crater in the comet's surface and collecting observations of the ejecta and newly exposed cometary interior with a companion flyby spacecraft. Deep Impact is the eighth mission in NASA's Discovery Program, following NEAR-Shoemaker, Mars Pathfinder, Lunar Prospector, Stardust, Genesis, CONTOUR, and MESSENGER. The project is organized as a team between the principal investigator, Dr. Michael A'Hearn of the University of Maryland; the science team of 11 other prominent experts on comets, remote sensing, and impact physics; the industrial partner, Ball Aerospace and Technologies Corp.; and the Jet Propulsion Laboratory as the NASA lead center.

The Deep Impact cratering experiment targets the nucleus of comet Tempel 1 near the time of perihelion for its 2005 apparition. This is accomplished by launching two joined spacecraft (flyby spacecraft + impactor) in December 2004/January 2005 to approach the comet in early July 2005. Using spacecraft optical observations of the comet and conventional ground-based navigation techniques, the joined spacecraft are maneuvered as close as possible to a collision trajectory with the nucleus of Tempel 1, and the impactor is released 24 h before impact. Figure 1 shows the two spacecraft at impactor release.

The impactor, a battery-powered spacecraft with a dry mass of 364 kg, observes the approaching nucleus with an optical camera and maneuvers itself to a collision course toward the lighted portion of the nucleus. After separation from the impactor,

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the flyby spacecraft maneuvers to delay and deflect its flight path toward the nucleus so that it can observe the impact, ejecta, crater development, and crater interior during a 500-km flyby of the nucleus that occurs about 14 min after the impact. The flyby spacecraft carries a remote sensing payload of two instruments for imaging and infrared spectroscopy. Close-in observations of the nucleus by the impactor camera are sent to the flyby spacecraft by a radio link in the last minutes before impact. The flyby spacecraft sends the highest priority scientific and engineering data to the ground in realtime during the encounter and also records the primary data sets for later playback. Simultaneous observations of the comet before, during, and after the impact are also conducted from ground and space-based observatories as an essential part of the total experiment. All scientific and supporting engineering data is archived for future use by the scientific community. Figure 2 shows an overview timeline for the mission.

The Deep Impact mission was originally proposed to launch in January 2004, using a 1-year Earth-to-Earth trajectory and an Earth flyby to initiate a direct 6-month transfer to intercept the comet. In March 2003, NASA approved a 1-year launch delay to allow more time for delivery of the spacecraft hardware and system-level testing. The mission now uses essentially the same 6-month direct trajectory to the comet that was the final trajectory segment of the 2004 mission. Although some of the launch conditions now change, the launch energy and launch mass capability are nearly identical for use of the Delta II 7925 launch vehicle. As well, the approach conditions at Tempel 1 are unchanged, so the original designs for the approach and encounter phases of the mission are unaffected.

2. The Target: Comet Tempel 1

Tempel 1, officially designated 9P/Tempel 1, is a periodic comet with a current orbital period of 5.5 years and an inclination of 10.5°. It was first discovered in 1867 by Ernst Tempel in Marseilles, France. Gravitational interactions with Jupiter near aphelion have changed the comet's orbit over time, and it was not observed between its 1879 and 1967 apparitions. Orbital elements for the 2005 apparition are given in Table I (Yeomans *et al.*, 2005). The descending nodal crossing (1.506 AU on 7 July 2005) is quite close to perihelion and allows a fairly low-energy intercept trajectory to depart Earth in late December 2004/January 2005, with favorable geometry for Earth-based observing as the comet approaches perihelion. Tempel 1 is observable from Earth throughout the mission, with the solar elongation never less than 95° (on the first launch date) and reaching opposition on 4 April 2005.

Regular observations of the comet have been conducted by the Science Team and cooperating astronomers since before the 2000 apparition (perihelion 3 Jan 2000) to gather information on characteristics of the comet to support the engineering design of the mission and plans for in-flight observations (Meech *et al.*, 2005). Analysis of these data is homing in on estimates of the nucleus albedo, mean radius and axial

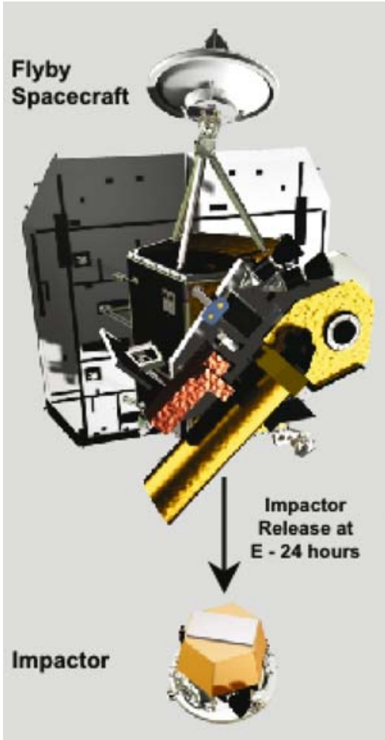

Figure 1. The Deep Impact flyby spacecraft and impactor shown at the time of impactor release, 24 h before the intended impact on comet 9P/Tempel 1.

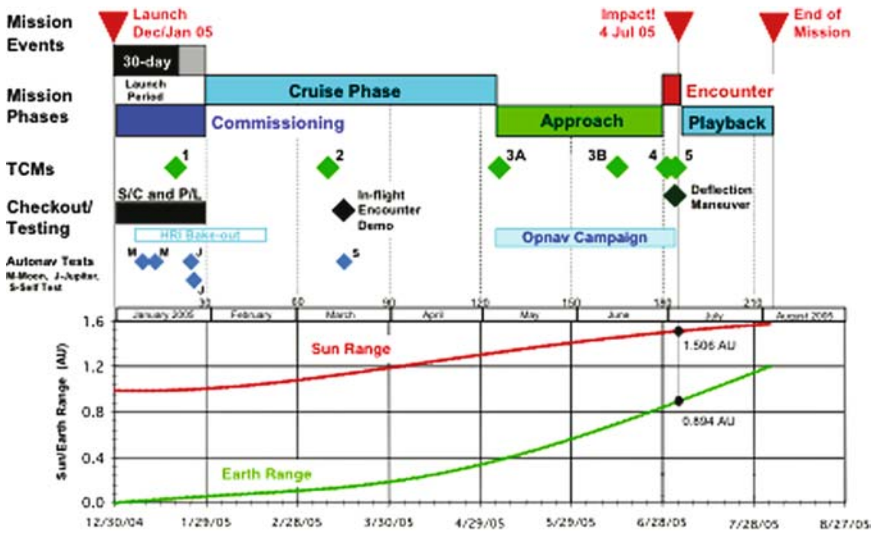

Figure 2. Timeline for the Deep Impact mission, based on the earliest launch date of 30 December 2004.

TABLE I
Tempel 1 orbital elements for the 2005 apparition.

Epoch	9 July 2005, 00:00:00 ET
Semi-major axis	3.1215288 AU
Eccentricity	0.5174906
Inclination	10.53009°
Ascending node	68.93732°
Argument of perihelion	178.83893°
Perihelion distance	1.5061670 AU
Perihelion epoch	5 July 2005, 07:34:02 ET
Coordinate system	Ecliptic and Mean Equinox of J2000
Astronomical unit (IAU)	149597870 km

ratio, rotation period, and pole direction. The current estimate of the nucleus mean radius is 3.25 km for an albedo of 4%. For the assumption that the nucleus has a prolate spheroid shape, current data suggest a large axial ratio of 3.2, as compared to Halley (2.0) and Borrelly (2.6). Based on many observations attempting to define the magnitude and phasing of the nuclear light curve, a rotational period of about 41.85 h is suggested (Belton *et al.*, 2005).

3. Alternate Targets

Comet Tempel 1 was selected as the target for the Deep Impact mission after a study of several potential targets that were available for launches from mid-2003 to September 2004, the time period required by the third NASA announcement of opportunity for the Discovery Program. Beginning in early 1998, this study looked for comets that could be reached for low launch energies ($\leq$15 km^2/s^2, twice the injection energy per unit mass), in order to fly the greatest impactor mass. Favorable approach phase angle (require $< 70°$, desire $< 45°$), approach speed (require 10–15 km/s), Earth viewing conditions (desire distance < 1 AU and elongation $> 90°$) at impact, encounter solar distance (desire 1.0–1.5 AU), and nucleus size (require radius $\geq$ 2 km) were also important considerations.

Two of the targets studied, asteroids 3200 Phaethon and 4015 Wilson-Harrington, are considered probable extinct or dormant comet nuclei, but these were rejected because of the uncertainty on the result of an impact experiment if there may be no volatile material. Two comet targets, 2P/Encke and 73P/Schwassmann-Wachmann 3, were studied, but these were already targets of the ill-fated CONTOUR mission and were rejected. Comet 9P/Tempel 1 became an early contender in this study because it had favorable launch and encounter conditions and, at the time, it was the target for the US-French comet rendezvous mission study Deep Space 4/Champollion (later called Space Technology 4 or ST4), which was planned to reach the comet after perihelion in December 2005. The possibility that this rendezvous/sample-return mission, under the NASA New Millennium space technology program, could arrive to study the newly formed crater made the synergy between these missions very attractive. Unfortunately, the ST4 mission study was cancelled only weeks before Deep Impact was selected as the eighth Discovery mission.

Tempel 1 is the selected target for the mission because the 2005 apparition allows a spacecraft of over 1000 kg to be launched to meet the comet near its perihelion at a distance of less than one AU from Earth. The Sun–Earth–Comet angle of 104° at the time of impact is favorable for simultaneous viewing from Earth. The encounter conditions give an approach speed of 10.2 km/s to provide high momentum for the impactor and a phase angle of about 63°, which is acceptable for approach imaging to target the nucleus. The comet activity is considered modest and predictable, so that the dust hazard could be well characterized for the design of spacecraft shielding. Some of the alternate targets considered for the Deep Impact mission and the reasons that they were not selected are listed in Table II. Although trajectory

TABLE II

Alternate targets considered for the Deep Impact mission.

Comet	Reasons not selected
(3200) Phaethon (launch Feb 2004, encounter Jan 2005)	Comet heritage isn't definite, very high flyby speed (32 km/s)
(4015) 107P/Wilson-Harrington (launch Nov 2002, encounter May 2005)	Comet heritage isn't definite, launch date too early, long flight time
2P/Encke (launch Feb 2003, encounter Nov 2003)	Launch date too early, high launch energy (34 km^2/s^2), very high flyby speed (28 km/s), CONTOUR target
73P/Schwassmann-Wachmann 3 (launch Mar 2004, encounter May 2006)	Small nucleus, uncertain dust environment after comet split in 1995, CONTOUR target
4P/Faye (launch March 2004, encounter Oct 2006)	Larger phase angle on approach (74°), higher launch energy, long flight time, high Sun range (1.7 AU)
10P/Tempel 2 (launch Feb–May 2003, encounter Jan–Feb 2005)	Impact near conjunction, not observable from Earth, launch date too early
37P/Forbes (launch Mar 2004 with Earth flyby, encounter Sep 2005)	Higher launch energy (17 km^2/s^2), quite high phase angle (86°)
41P/Tuttle-Giacobini-Kresak (launch Feb–Mar 2004, encounter Apr 2006)	Small nucleus with erratic outbursts, higher flyby speed (15 km/s), longer flight time
49P/Arend-Rigaux (launch Jul 2004, encounter Apr 2005)	Higher phase angle, poorer Earth viewing (1.4 AU, elongation 70°), very low activity
58P/Jackson-Neujmin (launch Jan 2003, encounter Dec 2003)	Launch date too early, larger phase angle on approach (84°), small nucleus, poorer Earth viewing (1.9 AU)

opportunities to a number of comets existed in the time period originally considered for launch, a number of factors, including high launch energy, poor approach phase angle, poor Earth viewing, small nucleus size, and uncertain dust environment eliminated most of the potential targets.

4. System Overview

4.1. Launch Vehicle

The launch vehicle for Deep Impact is the Boeing Delta II three-stage rocket. Launch occurs from Cape Canaveral from late December 2004 to January 2005. The Delta vehicle provides a reliable capability and a moderate cost for delivering a sufficient impactor mass (require >350 kg) at the Tempel 1 launch opportunity. For the required launch energy to reach Tempel 1 near perihelion in 2005 (see trajectory and launch phase descriptions below), the Delta II can carry a spacecraft mass of approximately 1020 kg.

The project originally planned to use a "heavy" version of the Delta II with larger strap-on rockets to fly an impactor mass of up to 500 kg, but elected to save about \$6 million in launch vehicle cost with a lighter impactor. The heavy version had the greatest payload capability of the vehicles allowed by the Discovery guidelines. Launch vehicles smaller than the Delta were available, but could not carry sufficient payload.

4.2. Flight System (Flyby Spacecraft and Impactor)

The primary element of the flight system (Figure 3) is the flyby spacecraft, which carries and targets the impactor up to 24 h before the impact; provides the stable platform for remote sensing of the comet nucleus before, during, and after the impact event; and provides the communications node for storage and return of the scientific data to Earth.

As seen in Figure 3, the flyby spacecraft is made up of the five-sided bus, which houses most of the subsystems; the instrument platform; and the two panels of the solar array, which fold against the bus in the launch configuration. The impactor is attached partially inside the bottom side of the flyby and serves as the launch vehicle adapter, mounting on the Delta II third stage so that the flyby $+X$ axis is upward at launch. After separation from the third stage, the solar panels are deployed to form a flat array normal to the flyby $+Y$ axis. The instrument platform mounts on the $-Y$ face of the flyby bus, with the instrument boresights aimed at a 45° angle between the $+Z$ and $-X$ axes. When the impactor is released, springs push it away in the $-X$ direction, and most of the shielding to protect against comet dust impacts is located on the flyby bottom face.

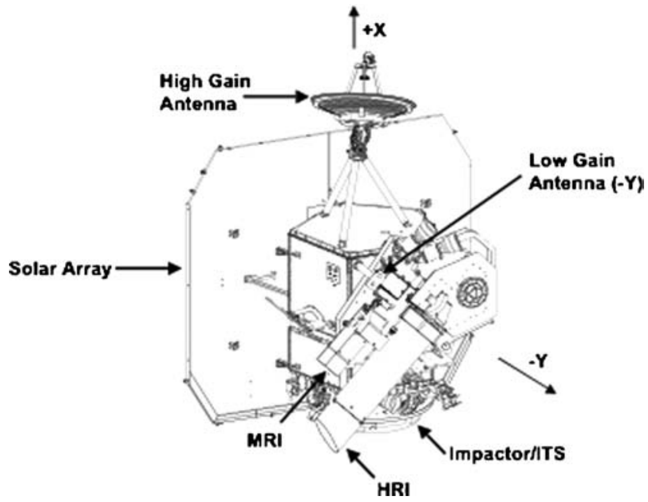

Figure 3. The Deep Impact flyby spacecraft and impactor shown mated in the cruise configuration.

The bus structure is made up of two modules: the propulsion module and the instrument module. The propulsion module is the backbone of the structure and houses all the components required for the propulsion subsystem and the components required on the flyby for the flyby/impactor separation. The instrument module houses all the components and wire harnesses required for other engineering subsystems. Most of the electronic components of the flyby spacecraft engineering subsystems (computers, star trackers, transponders, etc.) are redundant.

The solar array has two deployable wings, each one requiring a 36° deployment to reach the fully deployed position. The instrument platform provides the thermally and structurally stable mounting for all the alignment-critical components, including the flyby instrument complement, the two star trackers, and the inertial reference unit. The mechanisms on the flyby spacecraft are two gimbals for the high gain antenna, deployment and latch mechanisms for the solar arrays, and the flyby/impactor separation system. The mass of the flyby spacecraft at launch is about 601 kg, with a total flight system mass (fully fueled) of 973 kg. The flyby spacecraft carries about 86 kg of hydrazine propellant (including pressurant) for propulsive maneuvers, momentum control, and damping high rotational rates, such as at separation from the launch vehicle. Reaction wheels provide fine pointing control for imaging and in the cruise attitude for transit to Tempel 1. An S-band radio relay system provides communication with the impactor after release.

4.3. The Impactor

The impactor is a fully functional battery-powered spacecraft that operates on its own for 24 h after release from the flyby spacecraft. Its primary purpose is to open a large crater on the nucleus of Comet Tempel 1. To accomplish this, the impactor uses its autonomous navigation software to guide itself to an impact in a lighted portion of the nucleus using images from the impactor targeting sensor (ITS) to estimate targeting errors. Hydrazine thrusters are used for pointing and to correct the flight path. Because of its short operational life, the impactor has a single-string design, with many of its components being identical to those on the flyby spacecraft for cost efficiency. This includes the flight computer, inertial measurement unit, star tracker, and S-band radio relay. The impactor has a mass at launch of about 372 kg, including the hydrazine propellants (about 8 kg, including pressurant), and it also serves as the launch vehicle adapter, providing the mechanical interface to the Delta third stage.

4.4. The Payload

Three remote sensing instruments collect the scientific observations of Tempel 1 and the cratering event. The instruments also serve as navigation tools for setting up the impactor trajectory toward the comet, by ground navigation, and for pointing of the spacecraft toward the comet (Hampton *et al.*, 2005). The high-resolution instrument (HRI) combines a visual imager and infrared spectrometer with a 30-cm mirror in a Cassegrain telescope to provide high-resolution images and spectral maps of the nucleus and coma (2-mrad FOV, 2-μrad IFOV). The HRI is also the primary optical navigation sensor. The medium-resolution instrument (MRI) is a visual imager with a 12-cm mirror in a Cassegrain telescope to provide wider-field images, including full-nucleus context views at the closest distances (10-mrad FOV, 10-μrad IFOV). It also serves as the autonomous navigation sensor to support pointing of the flyby spacecraft on approach to the nucleus. The impactor target sensor (ITS) is identical to the MRI, except without a filter wheel, and serves as the autonomous navigation sensor on the impactor. In the final minutes before impact, it also provides close-in images of the nucleus to capture the topography at the impact site.

4.5. Autonomous Navigation Software

The autonomous navigation software (AutoNav) provides the capability on the impactor and flyby spacecraft to process images of the comet and update the ephemerides of the nucleus and the spacecraft (Mastrodemos *et al.*, 2005). Because the spacecraft ephemeris is well known from ground navigation processes, this effectively provides a target-relative ephemeris. This information is used to control timing and pointing on both spacecraft, and additionally to compute maneuvers to accomplish an intercepting trajectory for the impactor. AutoNav uses information from the attitude control system sensors (star trackers and inertial measurement units) on both the impactor and the flyby spacecraft, the MRI and HRI on the flyby and the ITS on the impactor.

The AutoNav software requires images from the MRI or ITS at 15-s intervals and attitude information associated with each image from the attitude control sensors. In return, AutoNav performs image processing, orbit determination, and maneuver computations to provide target relative position and velocity, ΔV magnitude and inertial direction for impactor targeting maneuvers, and timing adjustments for image sequence optimization on both spacecraft. The AutoNav capability is based on heritage from the Deep Space 1 and Stardust missions, which successfully encountered comets Borrelly (2001) and Wild 2 (2004), respectively (Bhaskaran *et al.*, 2004). On Deep Space 1, autonomous interplanetary navigation was also successfully demonstrated (Bhaskaran *et al.*, 2000).

Because of the large uncertainty in the comet's downtrack position, which cannot be resolved by ground-based optical navigation, autonomous navigation is an essential capability on the flyby spacecraft for pointing the instruments. Because of the cost of a "smart" self-guided impactor, a recurring issue on the project was whether a "dumb" impactor could be substituted for a lower cost. This question was always resolved in favor of the self-guided impactor, because numerous studies showed that late maneuvers by the impactor were essential to having a high confidence of hitting in a lighted area of an irregular nucleus, where the crater could be observed by instruments on the flyby spacecraft (Mastrodemos *et al.*, 2005).

5. Trajectory Description

5.1. Interplanetary Trajectory

A direct trajectory strategy, with about 6 months between launch and encounter, is used to launch Deep Impact in late December 2004 to January 2005. Figure 4 shows the interplanetary trajectory for Deep Impact for the first launch date. The original project baseline was to launch a year earlier in January 2004 and use a 1-year Earth-to-Earth trajectory segment to link up to the 2005 direct trajectory opportunity. The January 2004 launch strategy fit a shorter development schedule and provided more time in space for payload and spacecraft testing, but the project encountered hardware delivery delays that required a slip in the launch schedule by 1 year.

In terms of delivering a substantial science payload, the best opportunity for an intercept mission of Comet Tempel 1 is to arrive near the descending node of the comet's orbit (1.506 AU on 7 July 2005), which is very close to perihelion (5 July 2005). However, 4 July 2005 is a rough optimum for the encounter date when considering all the mission parameters, as it provides nearly the maximum injected mass (to allow a larger impacting mass). Later arrival dates do not provide much additional mass, and the approach phase angle and Earth range are degraded (therefore degrading approach observations, telecommunication rates, and Earth-based

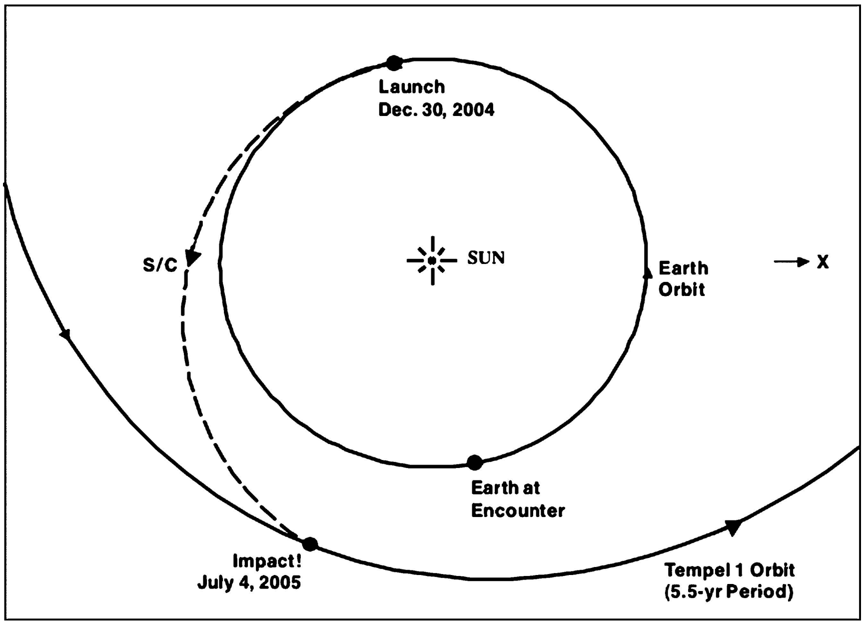

Figure 4. The Deep Impact interplanetary trajectory projected into the Ecliptic. A launch opportunity of 30 days begins on 30 December 2005, with a fixed arrival date at the comet of 4 July 2005.

observing). Earlier arrival dates provide a better approach phase angle and Earth range, but the mass capability falls off significantly and the encounter speed increases (resulting in either a larger deflection maneuver or less flyby observing time between impact and entering a shielded attitude for the coma crossing). Figure 5 shows the primary trade for the arrival date between the launch energy (for the optimal launch date) and the approach phase angle. While a lower phase angle is highly desirable for approach targeting, the autonomous navigation capability allowed selection of a later arrival date to provide for a larger impactor mass, to open a larger crater on the nucleus. For a 4 July encounter date, the optimum launch date is 9 January 2005 (minimum energy), and the best 21-day launch period extends from 30 December 2004 through 19 January 2005. Table III shows characteristics of the trajectory for the beginning, middle, and end of this primary launch period.

5.2. Encounter Trajectory

Although the Deep Impact spacecraft and comet P/Tempel 1 are both in curved orbits around the Sun, their high-speed intersection results in nearly straight-line relative trajectories, as shown in Figure 6. Two final targeting maneuvers by the flyby spacecraft place the impactor on a trajectory that ideally impacts the comet after

TABLE III

Deep Impact mission parameters 21-day primary launch period – 30 December 2004 to 19 January 2005.

Trajectory parameter	Open	Middle	Close
Launch (L)			
Launch date (2004/2005)	30 Dec	9 Jan	19 Jan
Launch energy $(km/s)^2$	11.58	10.79	11.75
Launch declination	-4.37°	-3.48°	-1.70°
Launch mass capability[a] (kg)	1018	1035	1015
Encounter (E)			
Encounter date (2005)	4 July	4 July	4 July
Impact speed (km/s)	10.20	10.28	10.36
Approach phase angle[b]	63.4°	62.5°	61.9°
Sun range (AU)	1.506	1.506	1.506
Earth range (AU)	0.894	0.894	0.894
Sun–earth-S/C angle	103.9°	103.9°	103.9°
Sun–S/C-earth angle	40.9°	40.9°	40.9°
Deflection ΔV[b] (m/s)	100.0	100.8	101.6
End of mission (EOM)			
EOM date (2005)[c]	3 August	3 August	3 August
EOM Sun range (AU)	1.570	1.573	1.576
EOM Earth range (AU)	1.203	1.206	1.208

[a]Single fixed flight system mass (976 kg, with ballasting on the third stage as required) will be used over the 21-day launch period (now extended to 30 days through 28 Jan 2005).
[b]At E−24 h. Deflection ΔV for post-impact imaging time of 800 s.
[c]At E+30 days.

release at E−24 h, but an accurate impact on the sunward side of the nucleus cannot be guaranteed without maneuvers closer to the target. After release, the impactor makes up to three small adjustments to this trajectory to correct any errors in the initial targeting and to aim for an impact on the lighted side of the nucleus. Each adjustment (impactor targeting maneuver or ITM) is computed by the AutoNav software. The impactor approaches the comet from a 63° phase angle, so the ITS does not see a fully illuminated nucleus.

After releasing the impactor, the flyby spacecraft deflects and delays its trajectory in order to safely pass by the nucleus and to have time to observe the impact and resulting crater. This deflection maneuver targets for a 500-km miss distance, which is selected to provide a survivable path through the inner coma dust environment while still allowing the HRI to meet the total resolution objective (7-m requirement, 3.4-m goal) for the last crater images. The flyby spacecraft configuration and dust

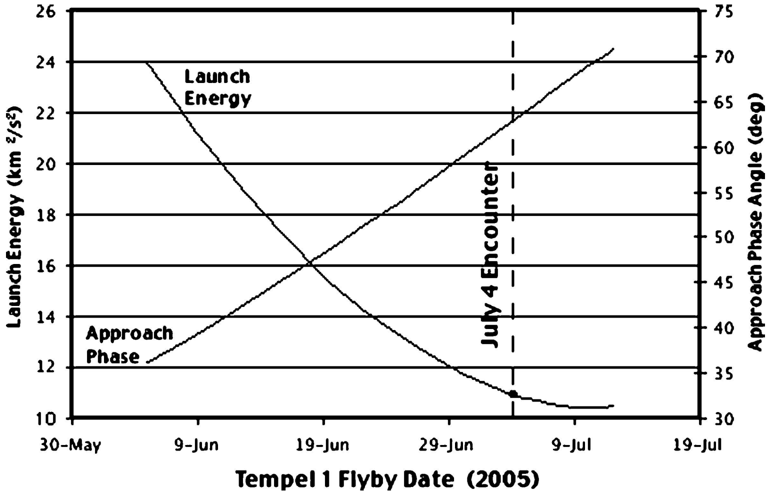

Figure 5. Arrival date trade space between launch energy for the optimal launch date and approach phase angle. The 4 July encounter date was selected to allow a massive impactor (originally 500 kg) with adequate margin for developing the flight hardware within the launch vehicle capability.

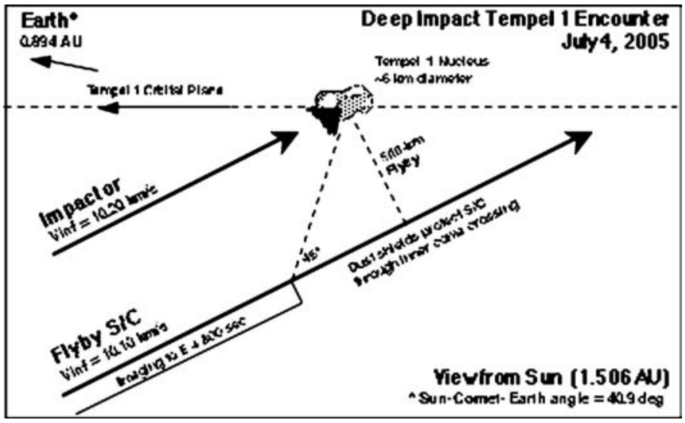

Figure 6. The flight path of the Deep Impact flyby spacecraft and impactor approaching the comet nucleus, as viewed from the Sun. The flyby spacecraft trajectory is targeted "below" the nucleus at a distance of 500 km to cross the comet's orbital plane after the closest approach.

shielding are designed so that MRI and HRI imaging can continue on approach to the nucleus until the spacecraft rotation reaches 45° to the relative velocity vector at about 700 km from the nucleus. At this orientation, the spacecraft control system then holds the spacecraft inertially in this "shield mode" for the passage past the nucleus, with the dust shielding providing protection to the critical subsystem components.

The deflection maneuver also slows down the flyby spacecraft, delaying closest approach until 850 s after impact, to allow time for imaging the impact event. Because imaging continues until the flyby spacecraft reaches a turn angle of 45° on the ideal trajectory, this strategy provides the science requirement of 800 s of observation time from impact until the shield mode attitude is reached. The science expectation is that the crater formation time is about 200 s, but with a high uncertainty, so the 800-s delay time provides a factor of four of conservatism.

The third component of the deflection maneuver is determined by the aiming point for the flyby trajectory, which determines its geometry relative to the Sun and Earth and to the orbit plane. For some small-body missions, a subsolar flyby is selected to provide the widest range of illumination angles, but the Deep Impact aimpoint is selected 90° to the Sun direction on the south ecliptic side of the nucleus. This provides two advantages: First, for a fixed solar array oriented parallel to the relative approach velocity, the direction of rotation to keep the imaging instruments pointed at the nucleus also keeps the Sun angle to the solar array constant at a maximum value during the flyby. Second, because the flyby spacecraft approaches the nucleus from "below," in the sense of its angular momentum vector around the Sun, this aimpoint means that the flyby spacecraft will pass through the comet's orbit plane after closest approach, as seen in Figure 6. This is considered to be an advantage in mitigating the possibility of impacting larger debris from the nucleus that may be co-orbiting around the Sun. The Giotto spacecraft suffered a large impact on approach to comet Halley in 1986, on a trajectory that crossed the orbit plane before closest approach. Although there is no good model for the size, volume density, and extent of such debris, it is thought to be more concentrated near the orbital plane. This approach geometry provides the greatest time for imaging and realtime data return before the crossing, and the crossing is at nearly the greatest distance possible from the nucleus for a 500-km closest approach.

The time of impact on 4 July 2005 is selected to provide highly reliable reception of the critical telemetry immediately before and after impact and excellent observing of the event from Earth-based observatories. These considerations favor use of the observatories at Mauna Kea, Hawaii, which lie between the NASA Deep Space Network (DSN) tracking sites at Goldstone, California and Canberra, Australia. The time of impact is scheduled after darkness at Mauna Kea and in the tracking overlap between the DSN tracking sites in a window between 0540 and 0635 UTC (Earth received time). This window allows for the possibility to further optimize the time of impact after launch to allow simultaneous observations by the Hubble Space Telescope (HST), which is periodically occulted from viewing the comet on each orbit. Because of variable atmospheric drag, the timing of HST orbital events cannot be predicted reliably months in advance, so the 55-min window allows the time of impact to be adjusted by maneuvers in the last 60 days before the encounter. The science team selects an impact time in this window that allows the best combination of observing by Earth-based and space-based observatories.

6. Mission Phases and Key Events

Six mission phases are defined to simplify description of the different periods of activity during the mission. As shown in Figure 2, these are the launch, commissioning, cruise, approach, encounter, and playback phases. Two time epochs are useful for defining activities and the boundaries of some of the mission phases. Launch (L) is the time of liftoff of the Delta II launch vehicle. Encounter (E) is the time of impact with Tempel 1.

6.1. Launch Phase

The launch phase begins with the start of the launch countdown and ends with stabilization of the flight system in a sun-pointed attitude under three-axis attitude control, which is expected within 27 h after liftoff. This phase includes the important event of initial acquisition of the spacecraft radio signal by the DSN. Launch occurs from the Cape Canaveral Air Force Station during a 21-day primary launch period beginning 30 December 2004, with a 9-day secondary launch period through 28 January 2005 providing additional launch opportunities. The primary launch period is selected to maximize the injected mass by minimizing the launch energy (11.75 km^2/s^2 on 19 Jan 2005). Because the flight system mass came in lighter than expected, nine secondary launch dates with reduced, but acceptable margin were added with a maximum launch energy of 14.24 km^2/s^2 on 28 January 2005. Two instantaneous liftoff times, separated by 39–40 min, are provided on each launch date to accommodate short interruptions that may occur late in the countdown.

6.2. Commissioning Phase

The commissioning phase extends from stabilization of the flight system under three-axis attitude control to 30 days after launch (L + 30 days). This is a period of initial operation, checkout, and calibration for the spacecraft and payload and includes an initial trajectory correction maneuver (TCM) to correct for launch vehicle injection errors.

Calibration of the payload and testing of the autonomous navigation system with some initial observations of the Moon are important objectives early in the commissioning phase. For the January 2004 launch of Deep Impact, the 1-year cruise between launch and the Earth flyby provided substantial time for checkout of the spacecraft subsystems, and the Earth flyby provided a unique opportunity for testing and calibration of the instruments and the AutoNav algorithms. With the 1-year launch delay, these activities must be prioritized and selectively scheduled during the commissioning or cruise phases, in order that the flight system and ground system reach full readiness at E−60 days for the approach and encounter phases of the mission.

Some initial science calibration measurements using the Moon are important to determine some characteristics of the payload and have been scheduled as early as 3 days after launch for the HRI and MRI to use the Moon as an extended and fairly uniform object. Similar measurements with the ITS are conducted as early as 13 days after launch after the impactor has been powered on and checked out. Tests of the AutoNav algorithms on the flyby spacecraft are also conducted using the Moon as a target. Subsequent tests of the 2-h encounter AutoNav encounter sequence use Jupiter as a target.

Because the HRI telescope structure is made with composite materials, it is subject to expansion if water is absorbed at the launch site in a brief period when the instrument is not purged with dry nitrogen. To provide for correction of the instrument focus due to this expansion, bakeout heaters provide the capability to warm the structure for up to 40 days and drive out the absorbed water. A focus test shortly after launch determines if this procedure is required.

6.3. Cruise Phase

The cruise phase begins 30 days after launch and ends 60 days before encounter with a duration of about 2–3 months, depending on launch date. Although a somewhat quieter period of transit between the busier commissioning and approach phases, this phase includes important science calibrations, an encounter demonstration test to run an encounter-like simulation on the flyby spacecraft, ground operational readiness tests, and a second TCM.

Monthly calibrations of the science instruments begin in this mission phase, with the three instruments observing a set of stars and nebula to further characterize the instrument performance and any time variation. To characterize the payload and attitude control system performance for the optical navigation imaging on approach to the comet, additional observations are collected.

Some initial long-range observations of Tempel 1 are attempted beginning in March 2005 for navigation purposes. The comet is at opposition from the spacecraft in early April, so the initial observations are at high sun angles and thermal control capabilities limit the observations to just a few minutes until the Sun–Spacecraft–Comet angle drops below 120° and the payload is fully shaded. The comet is also at opposition from Earth in early April (1.76 AU from the Sun), and ground-based observations are collected to update the comet's ephemeris for spacecraft targeting maneuvers in the approach phase.

With the fixed encounter date, the dates for cruise phase events beginning in late February 2005 are fixed on the calendar wherever possible to simplify scheduling. The date of TCM-2 is set for Thursday 10 March 2005, and fixed dates are planned for all subsequent maneuvers up to encounter. Some events early in the cruise phase, such as the end of the HRI bakeout, still vary with the actual launch date.

6.4. Approach Phase

The approach phase extends from 60 days before encounter until 5 days before encounter (E−60 days to E−5 days, 5 May to 29 June 2005). This is the period of intensive observations to detect the nucleus of Comet Tempel 1 using the HRI and then refine the spacecraft and comet ephemerides. It also includes regular science observations of the comet, payload testing, and two maneuvers (TCM-3A and 3B) to target the exact encounter time. The start of the approach phase at E−60 days is the approximate time at which it should be possible to clearly identify the comet nucleus in the coma background using the HRI. Daily images and spectra are collected to further characterize the activity and light curve of the comet. One goal of this study is to better define the rotational pole and phasing at encounter and understand the implications for the autonomous targeting of the impactor.

Two trajectory correction maneuvers in this phase correct the targeting of the flight system toward the comet and make final adjustments to the impact time, which can be adjusted within a 55-min window on 4 July 2005 to optimize observations by the Hubble Space Telescope (HST). HST is in a 96-min orbit around Earth that is periodically occulted from seeing the comet, and only about 50 min of observations are available on each orbit.

For most of this mission phase the sun-spacecraft-comet angle is greater than 120°, and periods of observation are limited to approximately 15 min every 4 h by thermal constraints. About 10 days before encounter, this angle falls below 120° and the HRI can observe the comet continuously while shaded from the sun. This allows a high volume of optical navigation images to be collected to support the final targeting maneuvers (TCM-4 and 5) in the encounter phase.

6.5. Encounter Phase

The encounter phase begins 5 days before and ends 1 day after the impact with Comet Tempel 1. This period includes the two final targeting maneuvers before release of the impactor, the 24-h impactor mission after release to achieve an impact on the lighted side of the comet nucleus, the deflection maneuver and subsequent imaging sequence for the flyby spacecraft during its close flyby of the nucleus with observations of the impact event and the resulting crater, and the playback of all the collected data.

Two final propulsive maneuvers complete the targeting of the impactor before it is released at E−24 h: TCM-4, executed at E−96 h, reduces the targeting error to well within the 30-km accuracy that is needed to provide a robust fuel margin for the impactor maneuver sequence after release. TCM-5, executed at E−30 h, provides a final, higher accuracy adjustment that has an accuracy of ~2 km. This further reduces the propulsive requirements on the impactor and provides a good chance of achieving impact if the impactor is unable to execute any targeting maneuvers.

The impactor is released at E$-$24 h with a relative separation speed of $\sim$36 cm/s that is accounted for in the final targeting. Five minutes after release, the impactor first begins to fly on its own, establishing inertial pointing, turning the ITS toward the comet and initiating a 64-kbps S-band telemetry link with the flyby spacecraft, which is maintained until impact.

After releasing the impactor, the flyby spacecraft regains attitude control and turns to the proper attitude for the deflection maneuver of about 100 m/s, which targets a safe, 500-km flyby of the nucleus and slows the spacecraft down to provide a 850-s delay between the time of impact and the time of closest approach. An imaging attitude toward the nucleus is then reestablished, and images and spectra of the comet and the impactor data are broadcast to Earth on the 200-kbps X-band telemetry link. On Earth, the largest, 70-m, antennas of the DSN are focused on collecting the critical scientific and engineering data.

Beginning 2 h before the predicted impact, the AutoNav software on both spacecraft begin processing ITS images of the nucleus to update the ephemerides of the comet and spacecraft for pointing control and maneuver computations. On the impactor, the first targeting maneuver (ITM-1) is computed and executed at E$-$100 min. ITM-2 follows at E$-$35 min, and the final targeting adjustment is executed at E$-$7.5 min to place the impactor on a path toward collision on the lighted portion of the nucleus. Beginning at E$-$4 min, the impactor is pointed along the relative velocity vector and images are returned to characterize the nucleus topography at the impact site (Klaasen *et al.*, 2005). Imaging continues to impact, but dust impacts may degrade the image quality or impactor pointing in the last minute. Subframed images of only the CCD central pixels are used to most rapidly read out and transmit the highest resolution images of the impact site.

On the flyby spacecraft the AutoNav results are used to maintain pointing toward the nucleus and to update the predicted time of impact. With its deflected flight path, the flyby spacecraft can better resolve the time-of-flight uncertainty in the comet's ephemeris. Ground processing of the optical navigation images provides an improved impact time estimate that is relayed up through the flyby spacecraft and the S-band link to the impactor to better control the timing of the final imaging sequence. On the flyby spacecraft, an autonomous update is used to initiate a rapid imaging sequence shortly before impact to best capture the impact event and to characterize the ejecta and formation of the crater. Imaging and spectral data are collected on the flyby spacecraft, which turns to keep the instruments pointed at the nucleus until it reaches a distance of about 700 km from the nucleus, at which time the spacecraft is locked into a shielding attitude for safe passage through the inner coma at a closest distance of 500 km from the nucleus. Pointing of the high-gain antenna to Earth is maintained through the imaging sequence and shielded attitude to deliver the critical scientific data to the ground at the highest 200-kbps telemetry rate. This shielded attitude prevents further imaging until the flyby spacecraft is safely beyond the greatest dust hazard. At 22 min after closest approach, the flyby spacecraft is turned to collect lookback images and spectra of the opposite side of the nucleus at a higher phase angle of 117°. Redundant playbacks of the encounter data and periodic lookback imaging continue into the final, playback phase of the mission.

6.6. Playback Phase

The playback phase begins one day after impact and continues to the end of mission at E+30 days (3 Aug 05). Completing the primary mission, this phase provides time to complete redundant playbacks of data stored during the encounter, to characterize the flyby spacecraft health after the encounter (including dust particle damage), and to leave the spacecraft in a known final configuration. Additionally, periodic lookback imaging of the comet is planned until 60 h after closest approach. A last calibration of the HRI and MRI is also conducted. Ground-based observations of Comet Tempel 1 continue indefinitely to allow monitoring of any changes in outgassing that would characterize evolution in the newly exposed surface layers.

7. Extended Mission Possibility

After the encounter, the flyby spacecraft is in a heliocentric orbit that has an orbital period of about 1.5 years. At this time, no follow-on mission is planned, but the orbital period means that the spacecraft re-encounters Earth in a distant flyby about 3 years after launch. If sufficient hydrazine remains in the fuel tank and other subsystems are healthy, this Earth flyby could be used as a gravity assist to another target. This possibility was first identified in early studies for the CONTOUR mission (Cornell University and Johns Hopkins University Applied Physics Lab, 1997).

Trajectory studies were conducted to identify small-body targets that could be accessible after the Earth flyby, under the following groundrules:

- no change to the baseline trajectory with a 4 July 2005 impact date,
- a minimum second Earth flyby altitude of 300 km, and
- reasonable expectations (100–150 m/s) of post-Tempel 1 maneuvering capability.

From several small-body targets identified in the initial search, five targets are possibly accessible within the spacecraft maneuvering capability and of great scientific interest. These include three comets (85P/Boethin, 103P/Hartley 2, and 10P/Tempel 2) and two asteroids (3200) Phaethon and (4015) 107P/Wilson-Harrington, which are considered possible extinct or dormant comet nuclei and which were considered as impact targets for the primary mission. Since the original studies, the discovery of numerous, very dark objects in cometary orbits has cast further doubt on brighter Phaethon being a dormant cometary nucleus, despite its association with a meteor stream. The Science Team selected Hartley 2 and Boethin as the targets of primary interest for more detailed study. Tempel 2 has a low probability of success, due to a higher maneuver requirement, and the asteroid targets have low approach phase angles that are actually bad for the Deep Impact spacecraft design, as the backside of the payload would be heated by the Sun. Observations of Hartley 2 have detected CO Cameron bands that have led to predictions of the abundance of CO_2, a prediction that could be tested with the Deep Impact instrumentation. Compared to Boethin, Hartley 2 has a longer flight time (encounter in October 2010), better Earth observing conditions (range 0.12 AU, Sun–Earth–Comet angle 121°), and a higher approach phase angle (108°). The Boethin encounter would occur earlier (December 2008), at a better approach phase angle (88°), but with less favorable Earth observing (range 0.89 AU, Sun-Earth-Comet angle 76°). Possible extended missions to these two targets are under study, but will depend on favorable interest from NASA, accurate launch conditions that conserve the propellant reserves, and the survival of the flyby spacecraft and payload during the passage through the inner coma at Tempel 1.

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